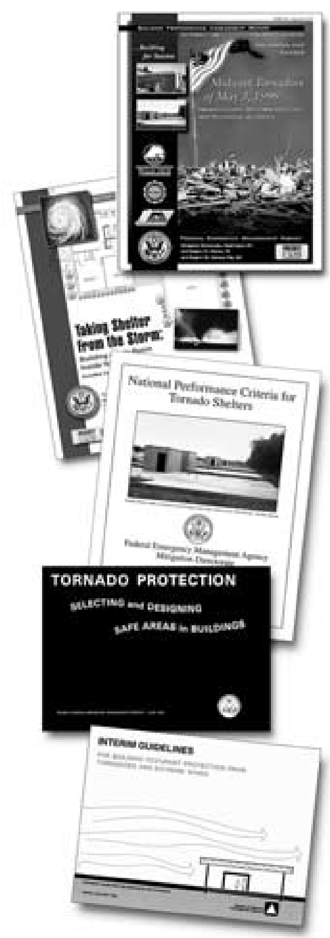
10 Design Commentary

The design and performance criteria specified in Chapters 5 and 6, respectively, were presented without discussion. This chapter begins with a summary of the existing guidance that has been published on high-wind design. Furthermore, this chapter contains commentary on a number of issues relating to the design and performance criteria and how the criteria should be used with ASCE 7-98 and other codes and standards.

10.1 Previous Publications



In October 1999, FEMA published FEMA 342, *Midwest Tornadoes of May 3, 1999: Observations, Recommendations, and Technical Guidance*. This document presents the observations, conclusions, and recommendations of the BPAT deployed to Oklahoma and Kansas after the May 1999 tornadoes. The conclusions and recommendations are presented to help communities, businesses, and individuals reduce the loss of life, future injuries, and property damage resulting from tornadoes.

In August 1999, FEMA published the second edition of *The National Performance Criteria for Tornado Shelters*. This document presents specific performance criteria for several tornado shelter parameters, including resistance to loads from wind pressure; resistance of walls and ceilings to impacts from windborne missiles; other loads (i.e., adjacent structures); access doors and door frames; ventilation; emergency lighting; sizing; accessibility; emergency management considerations; additional requirements for below grade shelters; multi-hazard mitigation issues; construction plans and specifications; quality control; and obtaining necessary permits.

In August 1999, FEMA also published the second edition of FEMA 320, *Taking Shelter From the Storm: Building a Safe Room Inside Your House*. This document provides homeowners with tools to evaluate the risk of high-wind events at their homes, planning strategies, and construction drawings for in-residence shelters. The construction drawings include plans for in-ground shelters, basement shelters, and aboveground shelters constructed of reinforced concrete, masonry, wood framing, and insulating concrete forms (ICF).

In June 1990, FEMA redistributed FEMA TR-83B, *Tornado Protection: Selecting and Designing Safe Areas in Buildings*. This document provides a review of three schools in the Midwest that were struck by tornadoes in 1974. Effects of high winds are discussed and specific case studies are presented, in addition to guidance for selecting the best available shelter in existing buildings and design parameters for new buildings that would offer protection from high-wind events.

In January 1980, FEMA published FEMA TR-83A, *Interim Guidelines for Building Occupant Protection from Tornadoes and Extreme Winds*. This document provides guidance for the design of high-wind shelters, including the forces generated by extreme winds. The focus is primarily for non-residential construction and includes designs for four hardened rooms (with construction options of reinforced brick masonry, reinforced concrete masonry units, and reinforced concrete). An example of a hardened room design for a school is also presented.

10.2 Commentary on the Design Criteria

The wind load provisions in ASCE 7-98 are based on wind tunnel modeling of buildings considering normal straight-line winds. It is believed that the results from these wind tunnel tests can be used to determine wind pressures from hurricanes. Because the gust structure of straight-line winds of hurricanes compared to tornadoes is believed to be significantly different, the wind tunnel results are not as applicable to tornadoes.

Until more research on the gust structure of tornadoes is conducted, wind engineers must use the same ASCE 7 provisions to calculate wind pressures from tornadoes as they do for other types of high winds. It is imperative that engineers exercise good judgment in the design of a building to resist tornadoes so that actual building performance falls within expected or desired ranges. It is important to note that other effects such as debris impact may control the design of an element rather than the direct wind pressure.

The design methodology presented in this manual is to use the wind load provisions of ASCE 7-98 modified only to the extent that the values of some factors have been specifically recommended because of the extreme nature of tornadic winds. If the values of all coefficients and factors used in determining wind pressures are selected by the user, the results would likely be overly conservative and not representative of the expected building behavior during the tornadic event.

10.2.1 Design Wind Speeds for Tornadoes

Historical data were the key tool used to establish wind speeds and zones associated with areas susceptible to tornado occurrence. The Storm Prediction Center (SPC) archives data for tornadoes, including the time and location of tornado occurrence and the intensity of the tornado.

The National Weather Service assigns an intensity F-scale measurement to each tornado occurrence. The F-scale was developed by Dr. T.T. Fujita in 1971 (Fujita 1971). The intensity F-scale is based on the appearance of damage to buildings and other structures. Dr. Fujita assigned a wind speed range to each F-scale level of damage and ascertained that the ranges represent the fastest 1/4-mile wind speeds. The F-scale and associated fastest 1/4-mile wind speeds are shown in Table 10.1. The table also shows the equivalent 3-second gust speed for each F-scale level. This conversion from fastest 1/4-mile to 3-second gust speed is obtained through the Durst curve given in the commentary of the ASCE 7-98. The wind speed ranges associated with the F-scale, which are based on subjective observation of damage, require some comments.

Table 10.1
Wind Speeds Associated With the Fujita Scale

FUJITA SCALE	FASTEST 1/4-MILE WIND SPEED (mph)*	3-SEC GUST WIND SPEED (mph)**
F0	40 - 72	45 - 77
F1	73 -112	78 - 118
F2	113 - 157	119 - 163
F3	158 - 206	164 - 210
F4	207 - 260	211 - 262
F5	261+	263+

Conversion: 1 mph = 0.447 m/s
* Fujita 1971
** Durst 1960 (ASCE 7-98)

Engineering analyses of damage since 1970 have shown that observed damage to buildings can be caused by wind speeds of less than 200 mph (Mehta 1970, Mehta et al. 1976, Mehta and Carter 1999, Phan and Simiu 1998). Prior to 1970, engineers associated wind speeds above 300 mph with F4 and F5 tornadoes. Although F4 and F5 tornadoes are intense and can cause devastating damage, the wind speeds traditionally assigned to these Fujita categories may well be too high (Minor et al. 1982). There is no evidence that wind speeds in tornadoes at ground level are higher than 200 mph, and certainly not higher than 250 mph. Some research meteorologists also agree with this conclusion. Hence, the wind speed zones are based on the occurrence of intense tornadoes, but the specified wind speeds are not necessarily related to the F-scale.

Data used for the development of wind speed zones are tornado statistics assembled by the NOAA SPC. The statistics used are for the years 1950 through 1998, almost 50 years of data. Tornado occurrence statistics prior to 1950 are available, though they are considered to be of lesser quality. During the 45 years from 1950 to 1994, a total of 35,252 tornadoes were recorded in the contiguous United States. Each of these tornadoes is assigned an F-scale level. The number of tornadoes, percentage in each F-scale level, and cumulative percentages are shown in Table 10.2. As noted in the table, less than 3 percent of the tornadoes are in the F4 category and less than 1 percent of the tornadoes are in the F5 category.

Table 10.2
Tornado Frequencies for the United States (1900-1994)

FUJITA SCALE	NUMBER OF TORNADOES	PERCENTAGE	CUMULATIVE PERCENTAGE
F0	11,046	31.3	31.3
F1	12,947	36.7	68.0
F2	7,717	21.9	89.9
F3	2,523	7.2	97.1
F4	898	2.6	99.7
F5	121	0.3	100
Total	35,252	100	

To develop wind speed zones, the occurrences of tornadoes over the 1950-1998 period are shown in 1-degree longitude-latitude maps. The number of F5 tornado occurrences and combined F4 and F5 tornado occurrences within 1-degree squares were tabulated for the country and used to produce the wind speed map in Figure 2-2. The average area in a 1-degree square is approximately 3,700 square miles. Tornado damage paths are less than 5 square miles on the average; thus, the area covered by a tornado on the ground is quite small compared to the size of a 1-degree square.

A 250-mph wind speed zone has been developed that covers all 1-degree squares that have recorded two or more F5 tornadoes in the last 49 years. This 250-mph zone also includes 10 or more combined F4 and F5 tornado occurrences during the 49 years. In Figure 2-2, the darkest zone covers the middle part of the United States, where the most intense tornado damage has occurred. It also includes large metropolitan areas of the midwestern and southwestern United States (e.g., Chicago, St. Louis, Dallas-Fort Worth). This area with specified wind speeds of 250 mph is designated as Zone IV.

A 200-mph wind speed area, Zone III, is developed using the statistics of F3 tornadoes. F3 tornadoes are less intense and are generally smaller (cover less area on the ground). The number of F3 tornado occurrences in a 1-degree square during the 1950-1998 period were determined for Figure 2-2. Most areas with 20 to 30 F3 tornado occurrences in a 1-degree square are already covered by Zone IV (250 mph wind speed). To be conservative, Zone III, with a wind speed of 200 mph, is extended to cover areas where more than five F3 tornadoes were identified within a single square. This zone extends along the gulf and lower Atlantic coastal areas to include hurricane winds (see Section 10.2.2). There are a couple of 1-degree squares in New York and Massachusetts that fall outside this zone even though they have more than five F3 tornado occurrences. They are considered outliers and have less than 10 F3 occurrences.

A 160-mph wind speed zone is designated as Zone II for the remaining areas east of the Rocky Mountains. The western border for Zone II follows approximately the Continental Divide. The wind speed of 160 mph covers all tornadoes of F2 or lesser intensity and is 75 percent higher than what is specified in ASCE 7-98.

In the areas west of the Rocky Mountains, there are relatively few tornado occurrences, and none have been assigned an intensity scale of F5. Over the past 49 years, only 2 tornadoes were assigned an intensity of F4 and only 10 were assigned an intensity of F3, over the entire region. It is concluded that wind speed of 130 mph is sufficient for this area designated as Zone I. This wind speed is about 50 percent higher than the basic wind speeds specified in ASCE 7-98 for the west coast states.

10.2.2 Design Wind Speeds for Hurricanes

Hurricane intensity is assessed using the Saffir-Simpson Scale of C1 through C5; hurricane category C5 is the most intense and the intensity decreases with the lower categories of storms. There are, on the average, five hurricanes recorded annually in the Atlantic; the landfalling hurricane average is 1.7. The National Hurricane Center of NOAA has archived data on hurricanes since 1900. Hurricane data include track, central barometric pressure, diameter of the eye, distance to hurricane force winds, maximum wind speeds, and storm surge height. The hurricane classification system has a range of wind speeds assigned to each category of storm as shown in Table 10.3.

The wind speeds associated with each category of storm are considered to be 1-minute sustained wind speeds (Powell et al. 1994). These wind speeds are converted to equivalent 3-second gust speeds using Figure C6-1 in the *Commentary* of ASCE 7-98 (Durst 1960). The 3-second gust wind speeds are shown in Table 10.3. The 3-second gust speed permits the development of a unified map for wind speed, as well as use of ASCE 7-98 for determining wind loads. The total number of hurricanes rated category C3, C4, or C5 that struck each U.S. gulf and Atlantic coast state during the period of 1900–1999 (100 years) were also identified and included in the preparation of Figure 2-2. The data show that no hurricanes of intensity C4 and C5 have made landfall north of the North Carolina coast. Also, during the last 100 years, only two category C5 storms have made landfall—an unnamed hurricane struck Florida in 1935 and Hurricane Camille made landfall in Mississippi and Louisiana in 1969. Based on those historical data, two wind speed zones are established for hurricane-prone coastal areas.

Table 10.3
Saffir-Simpson Hurricane Scale

SAFFIR-SIMPSON SCALE	1-MIN SUSTAINED WIND SPEED (mph) *	3-SEC GUST WIND SPEED (mph) **
C1	74 - 95	90 - 116
C2	96 - 110	117 - 134
C3	111 - 130	135 - 159
C4	131 - 154	160 - 188
C5	155 +	189+

Conversion: 1 mph = 0.447 m/s
* Powell 1993
** Durst 1960 (ASCE 7-98)

A design wind speed of 160-mph is specified for coastal areas north of North Carolina. This wind speed covers hurricane category C3 and less intense storms. It is assumed that hurricane winds affect areas up to 100 miles inland from the coastline. Zone II developed for tornadic winds matches this hurricane wind speed zone.

Along the gulf coast and the lower Atlantic coastal states (including North Carolina), a design wind speed of 200 mph is specified. This design wind speed matches the wind speed of Zone III established for tornadic winds. Hurricane winds are assumed to reach 100 miles inland from the coastline. Establishment of these wind speeds for hurricanes provides a unified map for design wind speeds for shelters in the 48 contiguous states.

For the islands of Hawaii and other territories, which are affected by hurricanes, design wind speeds are specified based on wind speed values in ASCE 7-98. The Territory of Guam uses a wind speed of 170 mph for normal design (ASCE 7-98). For shelter designs in Guam, the wind speed specified is 250 mph, the same as Zone IV. For other island areas where wind speeds specified in ASCE 7-98 range from 125 to 145 mph, a design wind speed of 200 mph is recommended for shelters, the same as in Zone III. For the islands of Hawaii, where the design wind speed specified in ASCE 7-98 is 105 mph, a design wind speed of 160 mph is recommended for shelters. This specification of wind speeds simplifies the use of the wind speed map and provides a reasonable factor of safety.

10.2.3 Wind Speeds for Alaska

The state of Alaska does not experience hurricanes and is not prone to a significant number of tornadoes. It does experience extratropical cyclone winds and thunderstorms. Since there are no specific records of extreme storms in Alaska, the shelter design wind speeds are based on contours shown on the map in ASCE 7-98. It is recommended that wind speeds for Zone II (160 mph) be used for areas that show ASCE 7-98 wind speeds of 110 mph or higher. For the interior areas where ASCE 7-98 wind speeds are less than 110 mph, the shelter design wind speed of Zone I (130 mph) is recommended.

10.2.4 Probability of Exceeding Wind Speed

Wind speeds specified on the map are obtained from available historical storm data, delineated wind speed contours from ASCE 7-98, and subjective judgment. The wind speed contours in ASCE 7-98 were obtained by dividing 500-year hurricane wind speed contours by "effective load factors" that are based on wind event return periods (ASCE 7-98, Section 66.5.4). This results in design-level wind speed contours that incorporate an implied importance factor for hurricane-prone areas. The implied importance factor ranges from near 1.0 up to about 1.25 (the explicit value in ASCE 7-93 is 1.05). ASCE 7-98 requires the use of an importance factor of 1.15 on loads if a building function is needed for post-storm operation or collapse of the structure is detrimental to a large number of people.

In addition, ASCE 7-98 wind speeds and loads are associated with allowable stress design. Additional safety against collapse is provided through the use of allowable stress in design or through load factors for limit state design. It is judged that the shelter design wind speeds and load combinations of ASCE 7-98 are associated with a 0.002 to 0.001 annual probability of severe damage or collapse (500- to 1,000-year mean recurrence interval [MRI]).

Community shelter designs should be based on wind speeds for low-probability events. The annual probability of exceeding the wind speed specified in the map varies widely because probabilities are based on historical data and subjective judgment. This is acceptable since data of storms also vary widely.

In the areas west of the Rocky Mountains and in Alaska, there are very few extreme storms, if any. In this area, the shelter design wind speeds will have a probability of exceedance of about 0.00033 (3,000-year MRI).

For hurricane regions, the annual probability of exceedance of wind speeds may be in the range of 0.0005 to 0.0001 (2,000- to 10,000-year MRI). For example, the Southern Florida region wind speed of 200 mph is associated with an annual probability of exceedance of 0.005 (2,000-year MRI), as obtained from the Monte Carlo numerical simulation procedure (Batts et al. 1980).

For tornadic regions, the annual probability of exceedance of wind speeds may be in the range of 5 x 10^{-5} to 1 x 10^{-6} (20,000- to 1,000,000-year MRI). For example, the Kentucky region wind speed of 250 mph is associated with an annual probability of exceedance of 1 x 10^{-6} (1,000,000-year MRI) (Coats and Murray 1985). This low probability of exceedance of wind speed in Zone IV is acceptable because the data used to calculate probability are of low quality.

It may be appropriate for a designer to develop a wind hazard model to obtain wind speeds associated with some low probability of exceedance for design purposes. Designers are cautioned that the quality of data along with appropriate statistical method should be taken into consideration to obtain the hazard model.

10.3 Commentary on the Performance Criteria

Windborne debris and falling objects are two of the risks that shelters are designed to mitigate against. Windborne debris and falling objects can be described in terms of their mass, shape, impact velocity, angle of impact, and motion at impact (i.e., linear motion or tumbling). The mass and impact velocity can be used to calculate a simple upper bound on the impact momentum and impact energy by assuming linear motion of the debris striking perpendicular to the surface. In this instance, the impact momentum is calculated using Formula 10.1, where W is the weight of the debris, g is the acceleration of gravity, and V is the impact velocity. For similar conditions, the impact energy can be calculated from Formula 10.2. I_m and I_e are the impact momentum and impact energy, respectively, for simple linear impacts perpendicular to the surface.

These equations provide reasonable estimates of impact momentum and impact energy for compact debris, where the length-to-diameter ratio is less than about 2, striking perpendicular to the surface. They also provide reasonable estimates for slender rigid body missiles striking on end, perpendicular to the surface when there is very little rotation of the missile. For off-angle impacts of compact debris (impacts at some angle to the surface), the normal component of the impact momentum and impact energy can be estimated with Formulas 10.1 and 10.2 if the velocity V is replaced by an effective velocity V´. Where V´ = V cos (Q) and the angle Q is measured relative to the axis normal to the surface.

Formula 10.1 Impact Momentum

$$I_m = (W/g)(V)$$

where: I_m = impact momentum
W = weight of debris
g = acceleration of gravity
V = impact velocity

Formula
Impact Momentum

Formula 10.2 Impact Energy

$$I_e = (1/2)(W/g)(V^2)$$

where: I_e = impact energy
W = weight of debris
g = acceleration of gravity
V = impact velocity

Formula
Impact Energy

For slender, rigid-body missiles such as wood structural members, pipes or rods, where the length-to-diameter ratio is greater than about 4, the angle of impact and the motion characteristics at impact become very important. Research has shown that the normal component of the impact drops off more rapidly than a simple cosine function for linear impact of long objects because the missile begins to rotate at impact (Pietras 1997). Figure 10-1, based on data from Pietras 1997, shows the reduction in normal force as a function of angle as compared to a cosine function reduction. For tumbling missiles, the equivalent impact velocity has been estimated using a complex equation (Twisdale and Dunn 1981, Twisdale 1985).

The impact of windborne debris can apply extremely large forces to the structure and its components over a very short period of time. The magnitude of the force is related to the mass of the object and the time of the deceleration as the missile impacts a surface of the shelter. The magnitudes of the forces also depend on the mechanics involved in the collision. For example, inelastic crushing of the wall or the missile will absorb some of the impact energy and reduce the force level applied to the structure. Similarly, large elastic or inelastic deformation of the structure in response to the impact can increase the duration of the deceleration period and hence reduce the magnitude of the impact forces. For a perfectly elastic impact, the impulse force exerted on the structure is equal to twice the impact momentum since the missile rebounds with a speed of equal magnitude to the impact velocity but in the opposite direction. For a perfectly plastic impact, the missile would not rebound and the impulse force would be equal to the impact momentum.

Figure 10-1
Variations of impact impulse as a function of impact angle.

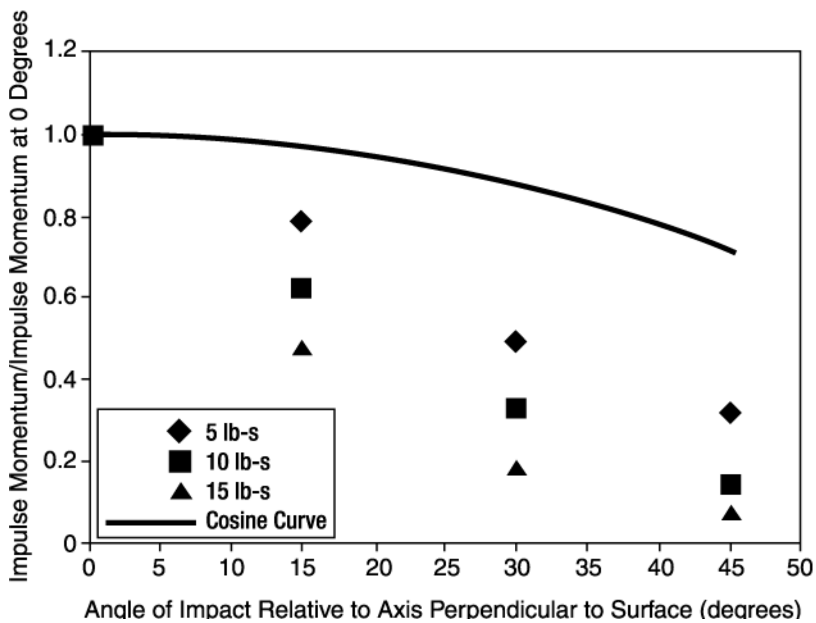


Figure 10-2 illustrates the impulse loading applied by a 4.1-lb Southern Yellow Pine 2x4 (nominal) missile striking a rigid impact plate at a velocity of 42.3 fps (21 mph). Note that the entire impulse force is applied over a period of 1.5 milliseconds and the peak force approaches 10,000 lb. Similar tests with a 9-lb wood 2x4 at 50 fps (34 mph) generated peak forces of around 25,000 lb. The dotted (raw) line represents the measured impulse force and includes some high-frequency response of the impact plate. The signal has been “filtered” to remove the high-frequency response of the impact plate and illustrate the expected impulse forces time history.

Impact test results for Southern Yellow Pine 2x4 members of various mass striking the impact plate at different velocities illustrate the complex nature of the impact phenomenon (Sciaudone 1996). Figure 10-3 compares the impulse force measured with the impact plate against the initial momentum of the missile. At low velocities, the impulse is characteristic of an inelastic impact where the impulse is equal to the initial momentum. This is likely due to the localized crushing of the wood fibers at the end of the missile. As the missile speed increases (initial momentum increases), the impulse increases toward a more elastic impact response because the impulse force increases to a value, which is substantially greater than initial momentum.

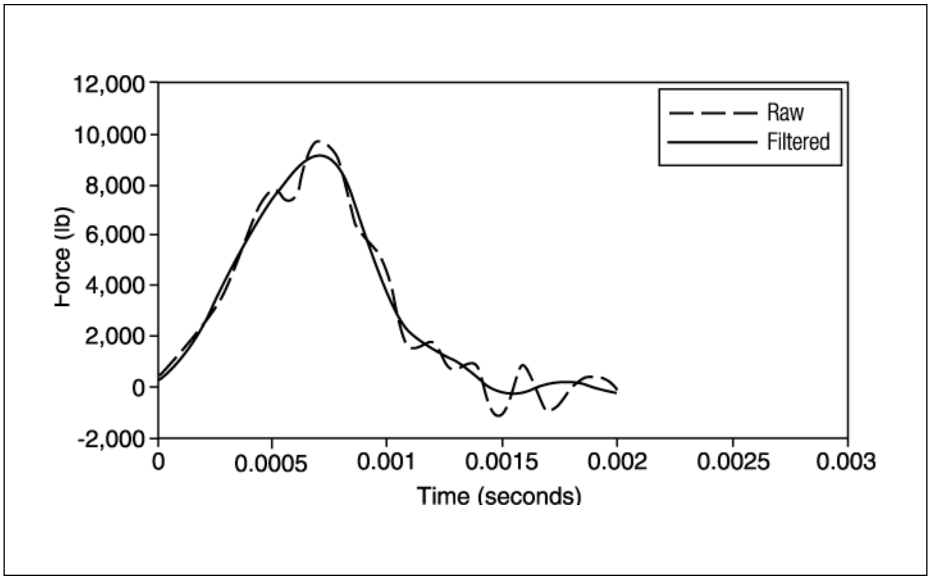


Figure 10-2
Raw and filtered forcing functions measured using impact plate for impact from a 4.1-lb 2x4 moving at 42.3 fps (Sciaudone 1996).

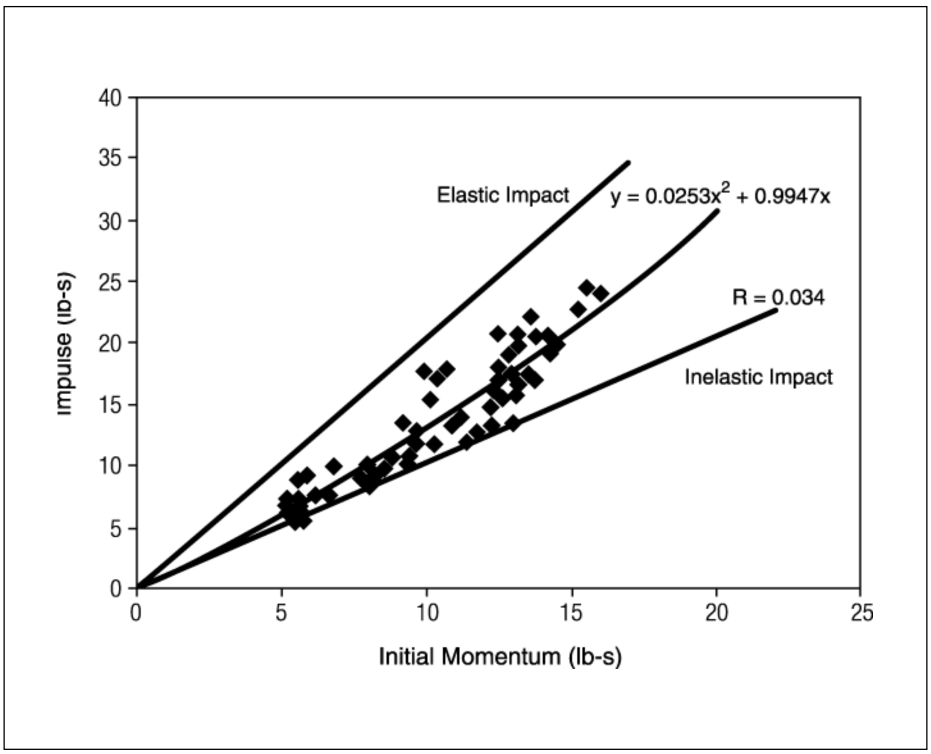


Figure 10-3
Impulse as a function of initial missile momentum for 2x4.

Design considerations should include local failures associated with missile perforation or penetration, as well as global structural failure. Sections 6.2.3 through 6.2.7 of this manual provide discussions that center on local failures. Global failures are usually related to overall wind loading of the structure or the very rare impact of an extremely large missile. Falling debris such as elevated mechanical equipment could cause a buckling failure of a roof structure if it impacted near the middle of the roof.